An Assessment of the High-gain Streckeisen STS2 Seismometer for Routine Earthquake Monitoring in the United States

D. E. McNamara, R.P. Buland and H.M. Benz
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Summary

Objective. In this document we report the results of a study to determine if the Streckeisen STS2 high-gain seismometer is appropriate for use by the United States Geological Survey's (USGS) Advanced National Seismic System (ANSS) for routine earthquake monitoring in the United States (US).

Issue. At issue is whether the high-gain STS2, with a sensitivity of 20,000 volts/meter/sec, can produce on-scale recordings of earthquake activity within the continental US, or whether the low-gain STS2, with a sensitivity of 1500 volts/meter/sec, is more appropriate for earthquake monitoring due to the relatively lower input velocity required for clipping the recording system. The test ANSS backbone station configuration, considered in this study consists of an STS2 broadband seismometer coupled to a Quanterra Q330 digitizer. The Q330 has a channel sensitivity of 4.19e5 counts/volt and a clip level of 8.38e6 = 8388608 counts (2e23) (20 volts). Therefore, an input ground velocity of only 0.001 m/sec will clip the high-gain system while an input ground velocity of 0.013 m/sec, a factor of 13 larger, is required to clip the lower-gain configuration.

Methods. In this report we use three different methods to examine the levels of input ground velocity expected during routine earthquake monitoring within the continental US. These methods include:
1. Computing peak ground velocity (PGV) expected at each ANSS backbone station from the USGS's 10% probability of exceedance in 30 years 1Hz spectral acceleration maps (Figure 1).
2. Modeling the amplitude of PGV at regional distances using Brune source scaling (Figure 2).
3. Analysis of the September 2004, M6 Parkfield earthquake at four broadband seismic stations within 1000km of the epicenter (Figures 2 and 3).

Recommendation: Based on the analysis of the three methods discussed above it is our recommendation that the low-gain STS2 is more appropriate for routine earthquake monitoring in the US. Method 1 indicates that if the high-gain configuration is used at all ANSS backbone stations, all can be expected to clip given the ground shaking levels expected in the next 30 years. Methods 2 and 3 indicate that an M6 will clip stations within approximately 875km of the epicenter. The high-gain STS2 is more useful for recording teleseismic events on a global scale but not suitable for on-scale recording of moderate to large earthquakes within the continental US.

Methods:

I. PGV computed from 1Hz Spectral Acceleration Map.

In this analysis we use the 1 Hz spectral acceleration 10% probability of exceedance in 30 years to calculate the expected PGV at each ANSS backbone station within the continental US (Frankel et al., 2002). The method includes the following procedures.

1. For each ANSS station determine *%g* from the 1 Hz spectral acceleration map (Figure 1) and convert to *g* (*g = 0.01* %g*) where *1g=980cm/s/s*.
2. Compute PGV in m/sec after (Newmark and Hall, 1982) where
   PGV = 594.8 * g / (2*π).
3. Compare PGV to clipping velocity of low and high-gain recording systems.

Results from this analysis are summarized in Table 1 and in figure 1. All high-gain STS2's will clip the Q330 digitizer given the input PGV computed from the 10% probability of exceedance spectral acceleration in the next 30 years. In contrast, 70% of the low-gain STS2's will clip in the regions with the highest expected input ground velocity. Stations in the mid-continent are not expected to clip (Figure 1). The high level of clipped stations for both the low and high gain STS2 seismometers indicates the importance of co-located low gain accelerometers if on-scale recording of all large motion is desired.

II. Brune Source Modeling

In this analysis we calculate expected shear-wave amplitude using the source scaling models of Brune (1970) and Brune (1971) for a range of distances (25-1200km) and magnitudes (M5-7). We then compare the modeled amplitude to the velocity required to clip both the high and low gain recording systems. (Figure 2). The method includes the following procedures.

1. For each Mw determine Mo from: $Mw = 0.667 \log(Mo) - 10.7$ (*Kanimori*, 1977).

2. For each Mo determine fault dimension from: $Mo = 2.29\sigma r^3$ dyne-cm
        (*Brune* 1970, 1971) where $\sigma = 1.0 \times 10^8$ effective stress.

3. For each fault dimension, determine source corner frequency from:

$$r = \frac{2.21\beta}{2\pi f c}$$ fault dimension in cm (*Brune* 1970, 1971).

        where β = shear wave velocity = 3.5km/s
              fc = source corner frequency

4. Find angular frequency (*fm*), by bisection, where Brune source spectrum is a maximum given ANSS short-period detection filters (0.5-12Hz).

5. For each source-receiver distance (from 25-1100 km), calculate Shear-wave PGV amplitude (*As*) in m/sec from:

$$As = \frac{Mo}{4\mu\beta} \bullet \frac{fmfc^2}{fm^2} + \frac{fc^2}{\Delta} \qquad \textit{(Brune 1970, 1971)}.$$

> where μ = rigidity
> fc = source corner frequency
> fm = effective frequency where amplitude is maximum
> β = shear-wave velocity (3.5km/s)
> Δ = source-receiver distance.

5. Apply attenuation to Shear-wave amplitude (As).

$$As = \frac{As}{\Delta^\gamma} \bullet e^{\dfrac{-\pi fm\Delta}{Q\beta}}$$

> where γ = geometric spreading (0.5)
> Q = Quality factor.
> Northern California (Erickson et al. 2004).
> $Q = 105 fm^{0.67}$

6. Multiply the modeled amplitude by the total sensitivity of the high-gain recording system (8.38e9 counts/m/s) and plot corrected PGV as a function of epicentral distance.

Results from this analysis are shown in figure 2 along with the input clipping velocities for both the high and low-gain systems. From figure 2 we see that a magnitude 6.0 will clip the high-gain system at distances less than about 875km while the low-gain system will clip at distances less than 150km. A magnitude 5.0 will clip the high-gain system at distances less than 175km.

III. M6.0 Parkfield Earthquake, September 2004

To verify the amplitude modeling results calculated in Method II we analyzed the amplitudes of the September 2004, M6 Parkfield earthquake (lat,lon) at four broadband seismic stations within 1100 km of the epicenter. Four stations that cooperate with the ANSS from the US, BRK and IU networks were used in the analysis. In each case, the M6.0 Parkfield earthquake did not clip any of the broadband stations. The stations used in the analysis include:

> HOPS: Hopland, Mendicino County California. BRK network.
> Digitizer: Quanterra Q380 recording at 20 samples/second.
> seismometer : STS1.

COR: Corvallis Oregon, US/IU network.
       Digitizer: Quanterra Q380 recording at 20 samples/second.
       Seismometer: STS1(sens 2.51e3 counts/volt)

WDC: Whiskeytown Dam, California, US/BRK network.
       Digitizer: Quanterra Q380 recordinga t 20 samples/second.
       Seismometer: Low-gain STS2 (sens 1500 counts/volt).

MOD: Modoc County California, BRK network.
       Digitizer: Quanterra QX-80 recording at 20 samples/second.
       Seismometer: STS1 (sens 2240 counts/volt).

The individual station instrument responses (Appendix 1) were deconvolved from the data and converted to displacement. We then convolved the data from each station with total response of the Q330 and high-gain STS2 (Appendix 1). For each station peak amplitude (PGV) was measured from the largest arrivals on the vertical component of motion (BHZ) which at regional distances is dominated the multiply reflected crustal shear-wave, *Lg*. PGV is then plotted as a function of epicentral distance (Figure 2) (Table 2).

From figure 2 it is apparent that the three stations closest to the Parkfield earthquake (HOPS, WDC, MOD) would have clipped if the high-gain recording systems were in use. In contrast, the stations did not actually clip with their current instrumentation and would not have clipped if the low-gain STS2 were deployed (Figure 2). Station COR, at 1003 km, would not have clipped either the low or high-gain system. Figure 3 shows the amplitude of the Parkfield M6.0 recorded at MOD at 667 km for three different instrumentation configurations. MOD currently has an STS1 (black line figure 3) and did not clip on the Parkfield earthquake. Figure 3 also demonstrates that a high-gain STS2 recording system would have been clipped by the Parkfield earthquake at MOD at a distance of 667 km..

Conclusions

Based on the results from this analysis it is apparent that the high-gain STS2 is not optimal for routine earthquake monitoring in the US. The gain level is sufficiently high that moderate size (M6.0) earthquakes would clip the Quanterra Q330 digitizer at distances less than 875 km. This is unacceptable if we hope to record these events on-scale. Instead, the high-gain STS2 is more appropriate for remote seismic stations where weaker ground motion are expected.

References

Brune, J., Tectonic stress and the spectra of seismic shear waves from earthquakes, J. Geophys. Res., 75, 4997-5009, 1970.

Brune, Correction, J. Geophys. Res., 76, 5002,1971.

D. Erickson, D., D. McNamara, H. Benz, Frequency-dependent Lg Q within the Continental United States, *Seism. Soc. Am. Bull*, 94, 1630-1643, 2004.

Frankel, A., Petersen, M., Mueller, C., Haller, K., Wheeler, R., Leyendecker, E., Wesson, R., Harmsen, S., Cramer, C., Perkins, D., and Rukstales, K. (2002). Documentation for the 2002 update of the national seismic hazard maps, U.S. Geological Survey Open-File Report 02-420, 39 pages.

Kanimori, The energy release in great earthquakes, J. Geophys. Res, 82, 2881-2987, 1977.

Newmark, N.M. and Hall, W.J., 1982, "Earthquake Spectra and Design" EERI monograph.

Figures

Figure 1: 10% in 30 years 1 Hz spectral acceleration for the US.
   A) Assuming Low-gain STS2 instrumentation (red triangles = clipped stations).
   B) Assuming high-gain STS2 instrumentation (red triangles = clipped stations).

Figure 2: Brune source modeled PGV vs. epicentral distance. Also plotted is the PGV measured at four stations from the September 2004 Parkfield M6.0 earthquake.

Figure 3: Seismogram of the Parkfield M6.0 recorded at MOD. Black line is the original seismogram using an STS1 seismometer. Magenta line is the waveform convolved with the low-gain recording system. Green line is the waveform convolved with the high-gain system.

Table 1: Percent Clip for standard and high-gain STS2 from Method I.

Sta	lat	lon	%g	g	PGV (m/s)	SG %clip	HG %clip
AAM	42.300999	−83.656998	1.330970	0.013310	0.0125997	0.944757	12.6018
ACSO	40.231998	−82.983002	1.736430	0.017364	0.016438	1.23256	16.4407
AHID	42.764999	−111.099998	13.802000	0.138020	0.130657	9.79702	130.679
ANMO	34.945999	−106.457001	4.496410	0.044964	0.0425654	3.19167	42.5725
BINY	42.199001	−75.986000	1.559670	0.015597	0.0147647	1.10709	14.7671
BLA	37.210999	−80.420998	2.192460	0.021925	0.020755	1.55626	20.7584
BLO	39.172001	−86.522003	2.566570	0.025666	0.0242965	1.82182	24.3006
BMN	40.431000	−117.222000	8.432590	0.084326	0.0798274	5.98567	79.8407
BOZ	45.599998	−111.633003	9.916620	0.099166	0.093876	7.03907	93.8916
BW06	42.778000	−109.556000	4.586710	0.045867	0.0434202	3.25577	43.4275
CBKS	38.813999	−99.737000	1.145350	0.011454	0.0108425	0.812999	10.8443
CBN	38.205002	−77.373001	1.408630	0.014086	0.0133349	0.999882	13.3371
CCM	38.056000	−91.245003	3.163960	0.031640	0.0299517	2.24586	29.9567
CMB	38.035000	−120.385002	9.530080	0.095301	0.0902169	6.7647	90.2318
COR	44.585999	−123.303001	9.505110	0.095051	0.0899805	6.74697	89.9954
DAC	36.277000	−117.594002	16.641701	0.166417	0.157539	11.8127	157.565
DUG	40.195999	−112.816002	5.698430	0.056984	0.0539444	4.04489	53.9533
DWPF	28.110001	−81.432999	0.653747	0.006537	0.00618872	0.464047	6.18975
ELK	40.744999	−115.238998	4.964200	0.049642	0.0469938	3.52372	47.0016
EYMN	47.945999	−91.495003	0.310897	0.003109	0.00294312	0.220683	2.94361
GOGA	33.410999	−83.467003	2.422660	0.024227	0.0229342	1.71967	22.938
HAWA	46.393002	−119.532997	5.147710	0.051477	0.048731	3.65398	48.7391
HKT	29.950001	−95.833000	0.816093	0.008161	0.00772557	0.579284	7.72685
HLID	43.561001	−114.418999	5.659060	0.056591	0.0535717	4.01695	53.5806
HOPS	38.993999	−123.071999	36.925400	0.369254	0.349556	26.2106	349.614
HRV	42.506001	−71.557999	1.748700	0.017487	0.0165541	1.24127	16.5569
HWUT	41.606998	−111.565002	9.699410	0.096994	0.0918198	6.88489	91.835
ISCO	39.799999	−105.612999	1.654140	0.016541	0.015659	1.17415	15.6616
JCT	30.479000	−99.802002	0.503462	0.005035	0.00476604	0.35737	4.76683
JFWS	42.914001	−90.248001	1.112710	0.011127	0.0105335	0.78983	10.5353
KNB	37.016998	−112.821999	4.696350	0.046964	0.0444582	3.33359	44.4655
LBNH	44.240002	−71.926003	2.280530	0.022805	0.0215887	1.61878	21.5923
LKWY	44.564999	−110.400002	12.156100	0.121561	0.115076	8.62871	115.095
LRAL	33.035000	−86.998001	2.224120	0.022241	0.0210547	1.57874	21.0582
LSCT	41.678001	−73.223999	1.604300	0.016043	0.0151872	1.13877	15.1897
LTX	29.334000	−103.667000	2.222410	0.022224	0.0210385	1.57752	21.042
MCWV	39.658001	−79.846001	1.584410	0.015844	0.0149989	1.12465	15.0014
MIAR	34.546001	−93.572998	2.096850	0.020968	0.0198499	1.4884	19.8532
MNV	38.432999	−118.153000	17.172800	0.171728	0.162567	12.1897	162.594
MOD	41.903000	−120.306000	8.412420	0.084124	0.0796365	5.97135	79.6497
MVU	38.505001	−112.210999	7.899620	0.078996	0.074782	5.60736	74.7944
MYNC	35.074001	−84.127998	3.033970	0.030340	0.0287212	2.15359	28.726

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NCB 43.971001 -74.223999 2.356310 0.023563 0.0223061 1.67257 22.3098
NEW 48.263000 -117.120003 3.619540 0.036195 0.0342645 2.56924 34.2702
NHSC 33.106998 -80.178001 3.245180 0.032452 0.0307206 2.30351 30.7257
OCWA 47.749001 -124.178001 16.503599 0.165036 0.156232 11.7147 156.258
OXF 34.512001 -89.408997 3.180920 0.031809 0.0301123 2.2579 30.1173
PAS 34.147999 -118.171997 37.812199 0.378122 0.357951 26.8401 358.01
PFO 33.609001 -116.455002 33.764099 0.337641 0.319629 23.9666 319.682
PLAL 34.981998 -88.075996 3.189070 0.031891 0.0301894 2.26368 30.1945
RSSD 44.119999 -104.036003 1.247570 0.012476 0.0118102 0.885558 11.8121
SAO 36.764999 -121.445000 43.401501 0.434015 0.410862 30.8075 410.93
SDCO 37.745998 -105.500999 2.562140 0.025621 0.0242546 1.81867 24.2586
SLM 38.636002 -90.236000 3.590330 0.035903 0.033988 2.54851 33.9936
SSPA 40.636002 -77.888000 1.393160 0.013932 0.0131884 0.988901 13.1906
TPH 38.075001 -117.223000 9.866430 0.098664 0.0934009 7.00345 93.4164
TPNV 36.948002 -116.249001 8.793650 0.087936 0.0832454 6.24196 83.2592
TUC 32.310001 -110.783997 2.316950 0.023170 0.0219335 1.64463 21.9371
WCI 38.229000 -86.293999 2.863830 0.028638 0.0271106 2.03282 27.115
WDC 40.580002 -122.540001 12.858200 0.128582 0.121723 9.12708 121.743
WMOK 34.737999 -98.780998 1.342820 0.013428 0.0127119 0.953168 12.714
WUAZ 35.516998 -111.374001 3.457260 0.034573 0.0327283 2.45405 32.7337
WVOR 42.433998 -118.637001 4.970230 0.049702 0.0470509 3.528 47.0587
WVT 36.130001 -87.830002 3.815320 0.038153 0.0361179 2.70821 36.1239
EGMT 47.950001 -109.779999 1.126660 0.011267 0.0106656 0.799733 10.6673
DGMT 48.580002 -104.199997 0.691208 0.006912 0.00654335 0.490638 6.54444
VKMN 48.220001 -96.410004 0.356017 0.003560 0.00337025 0.25271 3.37081
COWI 46.060001 -89.260002 0.589685 0.005897 0.00558227 0.418573 5.5832
GRMI 44.660000 -84.720001 0.939180 0.009392 0.00889078 0.666654 8.89226
OGNE 41.130001 -101.720001 1.013730 0.010137 0.00959651 0.719572 9.5981
SCIA 42.020000 -93.160004 1.104300 0.011043 0.0104539 0.783861 10.4556
PDNY 44.669998 -74.980003 2.698170 0.026982 0.0255423 1.91523 25.5466
MIME 45.660000 -68.709999 2.144410 0.021444 0.0203001 1.52216 20.3035
MONC 35.200001 -78.070000 1.583770 0.015838 0.0149928 1.1242 14.9953
ATAL 31.020000 -87.489998 1.479430 0.014794 0.0140051 1.05014 14.0074
GHTX 27.170000 -98.120003 0.288432 0.002884 0.00273045 0.204736 2.7309
SNSD 45.060001 -99.510002 0.750744 0.007507 0.00710694 0.532897 7.10812
ANND 47.880001 -100.239998 0.509268 0.005093 0.004821 0.361491 4.8218
AMTX 35.180000 -101.870003 0.955765 0.009558 0.00904778 0.678426 9.04928
BNMN 46.360001 -94.199997 0.442334 0.004423 0.00418737 0.31398 4.18806
BRMT 45.299999 -108.910004 3.247320 0.032473 0.0307409 2.30503 30.746
KCCO 38.759998 -102.790001 1.054920 0.010549 0.00998644 0.74881 9.9881
ERPA 42.130001 -80.089996 1.453010 0.014530 0.013755 1.03138 13.7573
SEKY 36.599998 -83.720001 2.942140 0.029421 0.0278519 2.08841 27.8565
CLKS 37.029999 -97.610001 1.406600 0.014066 0.0133156 0.998441 13.3178
NNNM 36.889999 -109.690002 1.343560 0.013436 0.0127189 0.953694 12.721
MNTX 31.697001 -105.382004 2.613080 0.026131 0.0247368 1.85483 24.7409
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Table 2: Parkfield PGV amplitude convolved with high-gain system response.

Sta	lat	lon	dist (km)	PGV(m/s)
MOD	41.9033	-120.305	667	0.00183
HOPS	38.9939	-123.071	421	0.00305
WDC	40.5800	-122.539	558	0.00190
COR	44.5857	-123.303	1003	0.00080

Appendix 1: Instrument responses

High-gain STS2 and Q330:
ZEROS   3
 0. 0.
 0. 0.
 0. 0.
POLES   5
  -3.70237E-02   3.70244E-02
  -3.70237E-02   -3.70244E-02
  -251.327 0.
  -118.634   423.065
  -118.634   -423.065
CONSTANT   4.05950E+17

HOPS:
ZEROS   3
 0. 0.
 0. 0.
 0. 0.
POLES   4
  -1.23400E-02   1.23400E-02
  -1.23400E-02   -1.23400E-02
  -39.1800   49.1200
  -39.1800   -49.1200
CONSTANT   3.88355E+12

WDC:
ZEROS   3
 0. 0.
 0. 0.
 0. 0.
POLES   5
  -3.70237E-02   3.70244E-02
  -3.70237E-02   -3.70244E-02
  -251.327 0.
  -118.634   423.065
  -118.634   -423.065
CONSTANT   2.92868E+16

MOD:
ZEROS   3
 0. 0.
 0. 0.
 0. 0.
POLES   4

```
  -1.23400E-02    1.23400E-02
  -1.23400E-02   -1.23400E-02
  -19.5900    24.5600
  -19.5900   -24.5600
CONSTANT     9.85368E+11

COR:
ZEROS   3
 0.  0.
 0.  0.
 0.  0.
POLES   4
  -1.23400E-02    1.23400E-02
  -1.23400E-02   -1.23400E-02
  -39.1800    49.1200
  -39.1800   -49.1200
CONSTANT     4.18246E+12
```
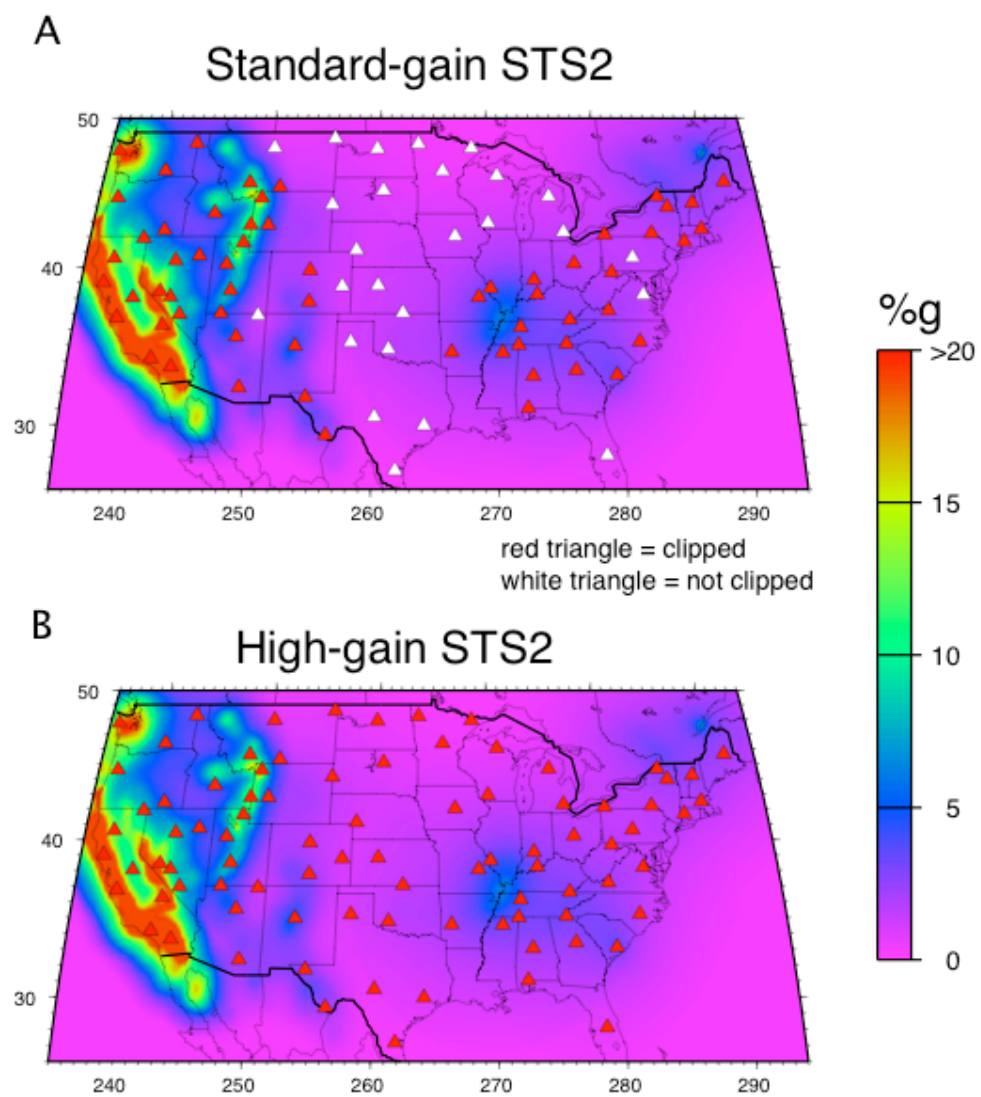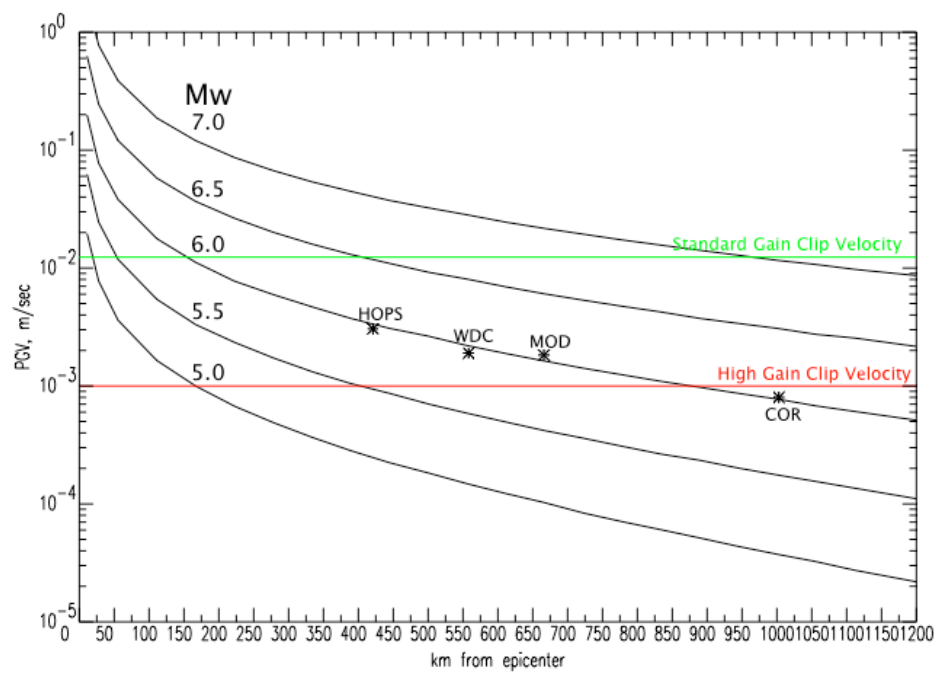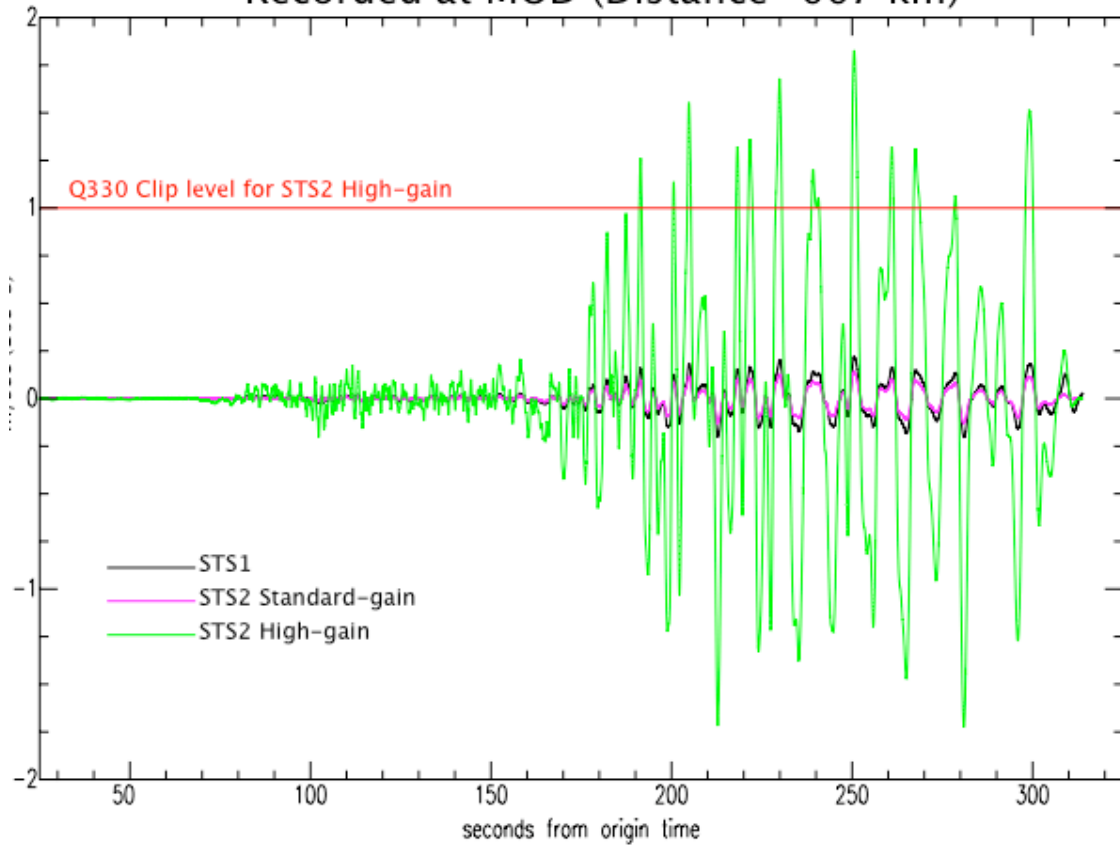
A Standard-gain STS2

red triangle = clipped
white triangle = not clipped

B High-gain STS2

%g

(Figure 1: McNamara et al., 2005)

Mw
7.0
6.5
6.0
5.5
5.0

PGV, m/sec

10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}

Standard Gain Clip Velocity
High Gain Clip Velocity

HOPS
WDC
MOD
COR

0 50 100 150 200 250 300 350 400 450 500 550 600 650 700 750 800 850 900 950 1000 1050 1100 1150 1200

km from epicenter

(Figure 2:McNamara et al., 2005)

Parkfield M6.0 9/28/2004 17:15:24
Recorded at MOD (Distance=667 km)

Q330 Clip level for STS2 High-gain

STS1
STS2 Standard-gain
STS2 High-gain

seconds from origin time

(Figure 3:McNamara et al., 2005)